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UNSOLVED PROBLEMS AND THE FUTURE OF ISM RESEARCH: INTERACTION BETWEEN MASSIVE STARS AND THE ISM

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RESUMEN

Las estrellas masivas interaccionan con el Medio Interestelar (MI) formando estructuras con una amplia variedad de tamaños y complejidades. Nuestro entendimiento de los procesos físicos involucrados en la formación de estas estructuras es incompleto. A menudo los problemas enigmáticos en la galaxia son manejados superficialmente asignándoles "dificultades observacionales". Sin embargo las estructuras interestelares en al Nube Mayor de Magallanes pueden ser estudiadas con gran claridad y detalle, permitiendo que los problemas del MI sean identificados sin ambigüedad. Discutimos algunos problemas intrigantes del MI referentes a burbujas producidas por vientos, remanentes de supernovas, superburbujas, cáscaras supergigantes y la fase caliente a gran escala del MI.

ABSTRACT

Massive stars interact with the ISM to form interstellar structures with a wide range of size and complexity. Our understanding of the physical processes involved in forming these structures remains incomplete. Often puzzling ISM problems in the Galaxy are hand-wavingly ascribed to "difficult observation" problems. However, interstellar structures in the Large Magellanic Cloud can be studied with great clarity and detail, allowing ISM problems to be unambiguously identified. We discuss intriguing ISM problems involving wind-blown bubbles, supernova remnants, superbubbles, supergiant shells, and the large-scale hot phase of the ISM.

Key words: **ISM: GENERAL – ISM: HII REGIONS – ISM: BUBBLES – ISM: SUPERNOVA REMNANTS – ISM: KINEMATICS AND DYNAMICS**

1. PRELUDE

Massive stars play an important role in the evolution of the ISM in a galaxy. They ionize and energize the ISM via stellar UV radiation and fast winds during their lifetime, and via supernova ejecta upon their demise. Depending on the distribution and formation history of massive stars, their interaction with the ISM can produce a wide array of interesting astronomical objects.

Not all interstellar structures formed by massive stars are well-understood. In the Galaxy, puzzling phenomena are often observed, but hand-waving explanations have been conveniently provided by "unknown distance," "heavy extinction," or "anomalous abundances." It is difficult to unambiguously separate unsolved ISM problems from badly observed physical parameters. The Large Magellanic Cloud (LMC), on the other hand, is at a known distance, has a small inclination angle, and a small amount of foreground extinction; therefore, it allows us to uncover more easily problems that cannot be solved with our current understanding of the ISM.

2. UNSOLVED ISM PROBLEMS

We discuss unsolved problems concerning ionized interstellar structures ranging from those produced by isolated stars (wind-blown bubbles and conventional supernova remnants) to those produced by OB associations (superbubbles) and multiple OB associations (supergiant shells). We also briefly discuss the hot phase of the ISM.

2.1. Wind-Blown Bubbles

Thirty years ago Johnson & Hogg (1965) reported two shell nebulae around Wolf-Rayet stars, NGC 2359 and NGC 6888, and suggested that the shells were formed by "ejection of matter from the star against the interstellar gas." The "continuous ejection of stellar mass" is called the "stellar wind" and these shell nebulae are called "wind-blown bubbles" in modern terminology. We have learned that the ambient medium for these two objects is probably stellar material lost previously during red supergiant or luminous blue variable phases, rather than interstellar material.

Models for wind blown bubbles have been presented by numerous investigators, most notably Weaver et al. (1977), who assume a homogeneous ambient interstellar medium. As stellar evolution becomes better understood, recent models have taken into account the history of stellar evolution and mass loss, and calculated the interaction between successive winds of varying strengths (García-Segura & Mac Low 1995; García-Segura, Mac Low, & Langer 1995). In general, bubbles blown by main sequence stars can be compared to Weaver et al.'s model, while bubbles around evolved stars should be compared to García-Segura & Mac Low's models.

Do observations of wind-blown bubbles agree with models? Based on optical observations of bubble dynamics and reasonable assumptions for the stellar wind strengths, observations of two main-sequence interstellar bubbles in M33 seem to agree with the Weaver et al. model (Oey & Massey 1994). However, models of NGC 6888, a Wolf-Rayet star bubble, show that the shell expansion velocity is too low for the observed stellar wind strength (García-Segura & Mac Low 1995). Could this discrepancy be caused by an overestimate of the stellar wind strength, perhaps caused by a clumpy stellar wind as suggested by Moffat & Robert (1994)?

The transfer of energy and mass between the hot and warm phases of the interstellar medium probably occurs through thermal conduction fronts where the two phases come into contact. An important ingredient of the Weaver et al. model is the conductive evaporation of the radiatively-cooled shell of swept-up ambient gas into the hot shocked wind. This conduction determines the mass of the hot interior, and so its radiative cooling and the evolution of the bubble. However, direct observations of the hot interior or the conduction front of bubbles are surprisingly scarce.

X-ray observations have detected only two stellar wind bubbles. NGC 6888 is the only bubble that has been unambiguously detected (Wrigge, Wendker, & Wisotzki 1994), and S308 is the only other bubble that has been even marginally detected (Wrigge 1995). ***Einstein*** observations showed "diffuse X-ray emission" in three other bubbles, but *ROSAT* observations have resolved that emission into stellar point sources (Chu 1994). Why are so few bubbles detected in X-rays? Is the density of the hot interior too low? Is the low density caused by a low conduction rate at the interface?

The first direct evidence for a conduction front has just been observed in the N V absorption lines in the spectrum of HD 50896, the central star of S308 (Boroson et al. 1995). However, the observed N V equivalent width is three times as large as expected from Weaver et al. model. Is this indicative of an anomalous abundance in the stellar wind? Is the model not applicable?

It is clear that many problems remain unsolved because of inadequate observations. Very few galactic bubbles are known and most of them suffer heavy extinction and confusion along the line of sight. The LMC bubbles are more suitable for detailed study and comparison with models, but have not yet been carefully observed. A systematic CCD imaging survey of LMC bubbles should be conducted. It is possible that some of the bubbles have long-exposure X-ray observations in the *ROSAT* archive, which would allow us to examine their hot gas content.

2.2. Supernova Remnants

Conventionally, supernova remnants (SNRs) are identified with three signatures: nonthermal radio emission, strong X-ray emission, and an enhanced [S II]/Hα line ratio. A SNR is usually described as confirmed only if all three signatures are observed. An object with only a subset of these signatures is usually described as a SNR *candidate*. However, recent observations of SNRs in the Magellanic Clouds have shown that bona fide SNRs do not necessarily possess all three of the conventional signatures.

SNRs may have only regional nonthermal radio emission. The best example is the SNR at the NE corner of the H II complex N44 (Shell 3 of Chu et al. 1993). The SNR was first diagnosed from its X-ray emission; follow-up optical images showed an enhanced [S II]/Hα line ratio along the entire shell periphery, and echelle observations revealed a typical SNR expansion pattern over the entire shell. However, ATCA radio observations showed only a half-shell (Smith et al. 1995). Why is there no nonthermal radio emission from the other half of the SNR shell?

Some SNRs do not seem to contain hot gas that emits in the X-ray. The SNR 0101–7226 in the SMC was identified originally by Mathewson et al. (1983), apparently showing all three SNR signatures. However, recent *ROSAT* observations have demonstrated that the X-ray source in SNR 0101–7226 is a point source coincident with a Be star (Hughes & Smith 1994). No diffuse X-ray emission is detected, although its radio spectral index is definitely nonthermal and SNRs with similar linear sizes (~25 pc) should be well above the detection threshold (Ye et al. 1995). Where does the hot shocked gas go?

2.3. X-Ray Bright Superbubbles

Diffuse X-ray emission has been detected in a large number of LMC superbubbles (Chu & Mac Low 1990; Wang & Helfand 1991). The observed X-ray luminosities exceed those expected from Weaver et al.'s models, so we have proposed that interior SNRs shocking the shell walls produce the excess X-ray emission. Two other explanations have also been proposed. The interstellar medium could be clumpy, and the interstellar clumps embedded in the hot interior of a superbubble might evaporate, increasing the density and so the X-ray emission. Alternatively, SNRs in the deep interior of a superbubble might hydrodynamically ablate the embedded cool, dense clumps and increase the density and X-ray emission from the superbubble (Arthur & Henney 1995). Which is the dominant mechanism that produces X-ray-bright superbubbles? Can these mechanisms be distinguished by observations?

At least for the X-ray-bright superbubbles in the 30 Doradus giant H II region, there is kinematic evidence for SNR-shocked clumps (Chu & Kennicutt 1994). On the other hand, the velocity offset between the interstellar high-ionization (C IV and Si IV) and low-ionization (S II, Si II, C II) absorption lines indicates the existence of SNR shocks at the approaching side of the shell (Chu et al. 1994). These results seem to support the mechanism of SNRs shocking shell walls. The situation is no clearer in other X-ray bright superbubbles, as no high-velocity material is detected in the Hα echelle observations, and no good UV interstellar absorption line observations are available yet.

Future high-quality, high-dispersion UV absorption line observations and high-resolution X-ray images are needed to differentiate the aforementioned three mechanisms for enhancing X-ray emission in superbubbles.

2.4. Blow-outs in Superbubbles and Supergiant Shells

Superbubbles (~50–200 pc diameter) and supergiant shells (~1000 pc diameter) are the largest interstellar structures in a galaxy. These shell sizes are comparable to or larger than the scale height of the gaseous disk, so it has been suggested that these bubbles blow completely out of the galactic disk (Mac Low, McCray, & Norman 1989). The hot gas in the shell interiors rises high above the galactic plane, forming a more or less patchy, hot halo, which subsequently cools and returns to the disk as high velocity clouds (e.g., Norman & Ikeuchi 1989).

However, recent models show that magnetic fields can effectively confine bubbles and sometimes prevent the occurrence of blow-outs (Ferrière, Mac Low, & Zweibel 1991; Tomisaka 1990, 1992). Furthermore, the existence of a low-density layer of gas (the Lockman H I and Reynolds H II components) extending to several hundred pc above the galactic plane makes it difficult for superbubbles or supergiant shells to break out into the halo (Heiles 1990). It is not certain when interstellar blow-outs do occur.

To study the blow-out phenomenon, we must first identify bubbles that have blown out. So far, blow-outs in the LMC have been identified by optical morphologies, e.g., radial filaments streaming away from the periphery of a shell or a starburst region, or curved filaments at large distances ($\gg$ radius) from the shell center. It has also been suggested that diffuse X-ray emission extending beyond the optical shell boundary implies an outflow of hot gas, or a blow-out. The superbubble N44 (Chu et al. 1993) and the supergiant shell LMC2 (Wang & Helfand 1991) are two good examples. Are these real blow-outs? Is there another independent, unambiguous physical property that can confirm the blow-out nature?

2.5. Hot Gas in the LMC

The strong absorption lines of C IV, Si IV and NV can trace regions of 10^5 K gas. As gas at this temperature lies at the peak of the cooling curve, it can only exist in interfaces between hot, 10^6 K gas and warm, 10^4 K gas. (Note that Si IV absorption lines can also be produced by photoionization, but the other two lines lie at higher energy, and so trace 10^5 K gas more cleanly.) Observations of these lines thus allow us to trace the very hottest gas at temperatures of 10^5 K or higher. Only a few objects observed by *IUE* lie away from large shell structures or early-type stars. Those few objects appear to lack high-ion absorption lines, suggesting that any hot LMC halo is not uniform, but associated with the large supershells (Chu et al. 1994).

Recent *ROSAT* observations of the LMC allow us to directly examine the hottest gas (Snowden & Petre 1994). There is obviously large-scale diffuse X-ray emission in the LMC. While some of the X-ray emission is confined in large shell structures such as superbubbles and supergiant shells, there is also a component that does not seem to correlate with any interstellar structure. Does this diffuse emission come from the disk or the halo? Is the hot gas produced locally or transported from large shell structures elsewhere via blow-outs?

3. EPILOGUE

The LMC provides an excellent laboratory for us to study interstellar processes. Many intriguing problems remain unsolved. While higher-quality data are needed in the future to improve our chance to solve the problems, it is also necessary to broaden our research methods to include the correlation of data taken at multiple wavelengths, and to study the massive stars alongside the interstellar medium. With the availability of the *HST, ROSAT, ASCA,* CTIO, and the possibly future *AXAF, FUSE,* and Gemini, these unsolved problems will not remain unsolved for too long.

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